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Gravity gradient technique to identify fracture zones in Palu Koro strike-slip fault

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Abstract

The forces acting upon a rock mass can result in physical changes on either side of the fault plane that are known as fracture zones. This tectonic activity will lead to a difference in the density of fracture zones from the density of surrounding rocks. This condition can be detected using gravity method. The changes of rocks density in contrast to fracture zones are relatively small, so a rigorous technique of gravity data processing to detect its presence is required. This research has developed and implemented the gravity gradient technique as one of the processing and acquisition techniques of gravity data which is found to have a high accuracy to detect the boundaries of rock density contrast changes. For the purposes of analyzing the gravity responses in identifying fracture zones, the characteristics of the gravity and its gradient responses of fracture zones in a strike-slip fault system were analyzed based on the forward and inverse modeling results. Furthermore, the gradient and gravity anomaly inversions were applied to the gravity data towards Palu-Koro strike-slip fault, a segment of the Palu City, Central Sulawesi, Indonesia. The measurement results show that the gravity gradient anomaly has a higher sensitivity compared to its gravity anomaly in detecting the fracture zones. In addition, the inversion result of the gravity gradient anomaly shows that the boundaries of lateral changes in the distribution of density contrast of fracture zones can be identified more accurately.

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Keywords: fracture zone; gravity gradient; density contrast.

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1. Introduction

The Earth rocks are very slowly but continuously moving and changing in shape. Rocks near the surface of the Earth behave in a brittle fashion and respond to large stresses by fracturing unless they are deformed slowly. In geology, faults occur at brittle rocks fracture, and there is displacement of one side of the fracture zone relative to the other side. The strike-slip fault is a type of fault in which the displacement on the fault has taken place along a horizontal direction. Such faults result from shear stresses acting in the crust.

A model of a strike-slip fault system can be constructed using three elements as shown in Fig. 1, i.e. a fault plane (fault core), fracture zone, and undeformed host rock [1]. The forces acting upon a rock mass will result in a fracture zone as can be found in the region of Palu Koro strike-slip fault. The fracture zones are characterized by density contrast changes due to secondary porosity associated with a fracture system or faulting. Fracturing in a rock mass will cause bulk density to decrease while rocks porosity increases, and thus makes the density of fracture zones differ from the surrounding rocks. The changes of rocks density in the fracture zones are relatively small. Therefore, it requires a rigorous technique of gravity data acquisition to detect its presence. The modeling of density contrast changes in the fracture zones using the gravity gradient technique results in a higher accuracy than when using the conventional gravity method in detecting the boundaries of rock density changes [2&3]. Vertical gradient information is also more sensitive than gravity itself especially in order to delineate the contacts of the geological structure [4&5].

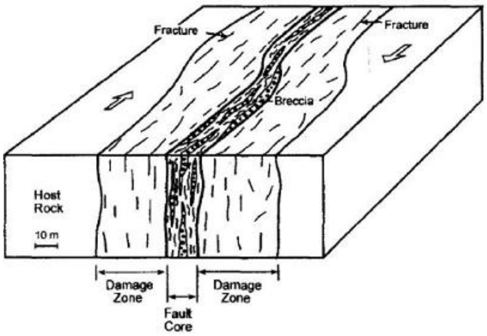


Fig.1. A model of a strike-slip fault system constructed by a fault core, fracture zone, and undeformed host rock [1].

2. Data and Method

In this research, the constructed strike-slip fault model as in Fig. 2a. Its consists of fracture zones in which the sides of the fault plane have a symmetrical form and the density contrast change decreases linearly with increasing distance away from the fault plane toward the fracture zones (-0.05 gr/cm^3, -0.04 gr/cm^3, -0.03 gr/cm^3, -0.02 gr/cm^3, -0.01 gr/cm^3 and - 0.005 gr/cm^3, respectively). The model is built upon the assumption that the fault zones are approximated by a set of rectangular prism cells.

The gravity anomaly responses of the strike-slip fault model can be estimated using eq. *(1)* [6].

$$\Delta g_z = G\Delta\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2}\mu_{i,j,k}\left[z_k \arctan\frac{x_i y_j}{z_k R_{ijk}} - x_i \log(R_{ijk}+y_j) - y_j \log(R_{ijk}+x_i)\right] \tag{1}$$

Where; Δg_z is gravity anomaly caused by a cube body; G is gravity constant, $\Delta\rho$ is density contrast of cube body; $\mu_{i,j,k} = (-1)^i (-1)^j (-1)^k$, coordinate x, y, z is border of cube body in x-axis, y-axis, and z-axis, and R_{ijk} is length between measurement station with body centre of coordinate.

Finally, the horizontal gradient responses (horizontal derivative from gravity data) in the x- and y-direction can be calculated by eq. *(2)*, whilst eq. *(3)* will be used to estimate the vertical gradient responses [7&8].

$$\Delta g_{xz} = -G\Delta\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \ln\left(y_i + R_{ijk}\right) \quad \text{and} \quad \Delta g_{yz} = -G\Delta\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \ln\left(x_i + R_{ijk}\right) \tag{2}$$

$$\Delta g_{zz} = G\Delta\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{i,j,k} \arctan\left(\frac{x_i y_i}{z_k R_{ijk}}\right) \tag{3}$$

The forward modeling results indicate that the vertical and horizontal gradient responses can detect the boundaries of the lateral changes in rock density more accurately. As shown in Fig. 2c and 2d, the edge of the fracture zones clearly appears from the gravity gradients in comparison to the gravity response (Fig. 2b). For analysis purposes, the Fig. 3 shows the responses of gravity and its gradients for section A1-A2. Based on this figure, it can be observed that the presence of fracture zones in a strike-slip fault system causes negative vertical gradient and gravity responses, whilst the fault plane and the boundaries of the fracture zones have the amplitude of horizontal gradient as well as second horizontal gradient responses with a symmetrical pattern but opposite in sign. Thus, these criteria can be used to identify the fracture zones.

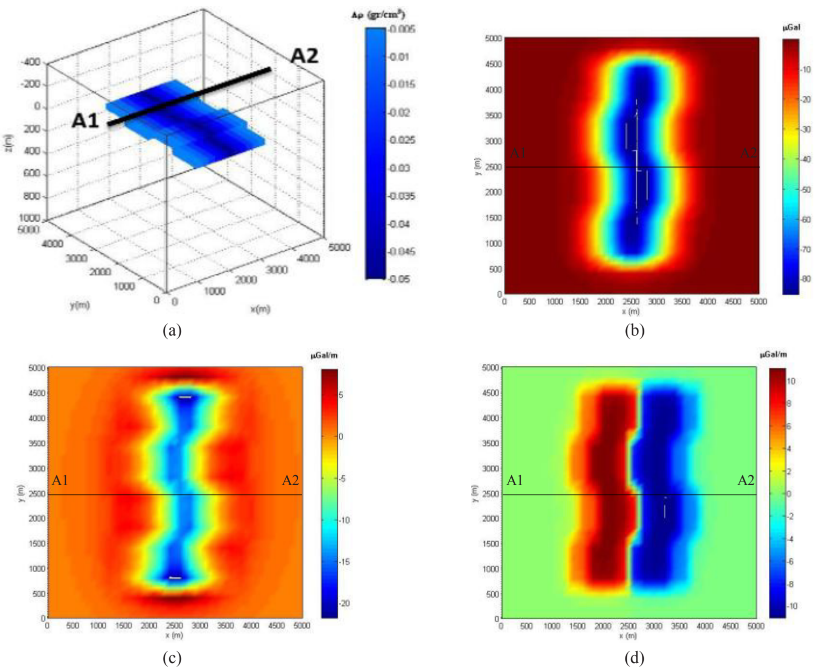


Fig.2. (a) Fracture zones model in a strike-slip fault system; (b) Gravity response of the model; (c) Vertical gradient response of the model; (d) Horizontal gradient response of the model.

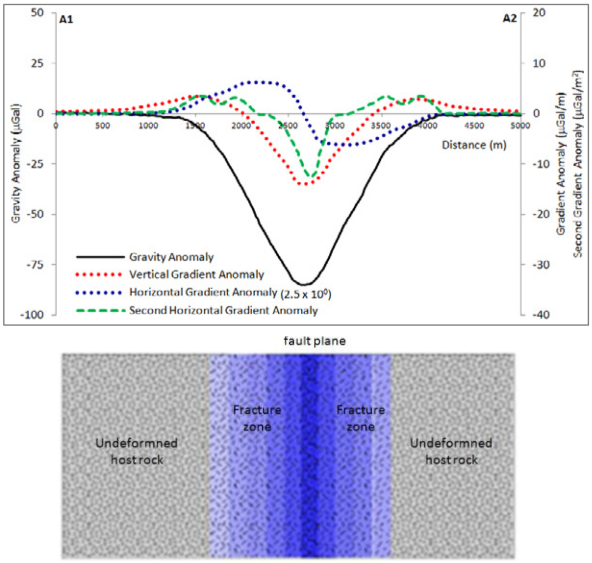
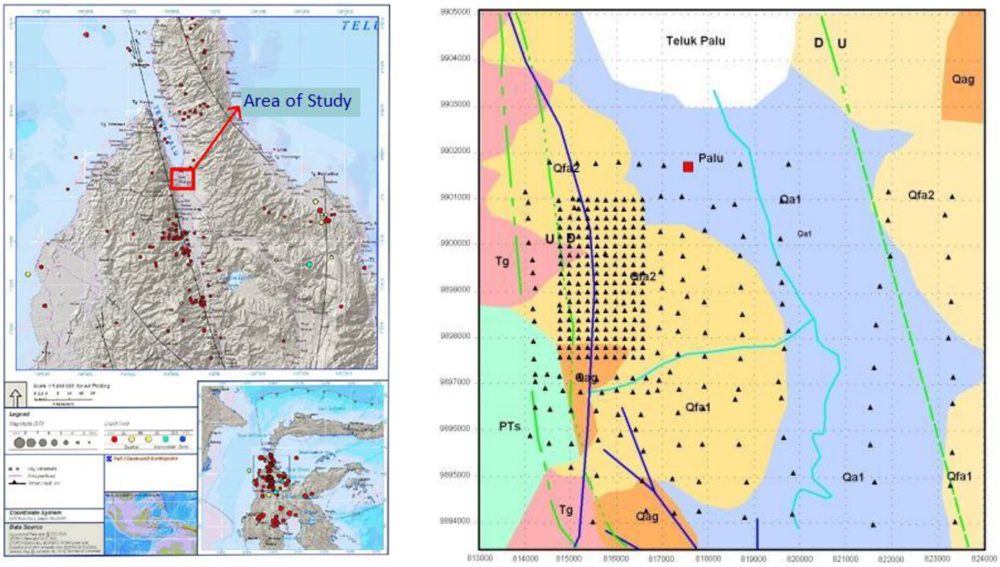


Fig. 3. Gravity and its gradient responses for section A1-A2 of a strike-slip fault model .

The Palu Koro fault region (Fig. 4) was selected as the study area based on the consideration that the Palu Koro fault is a fault with horizontal movement reaching 35 ± 8 mm per year [9]. This condition indicates that the region has high tectonic activity to cause the fracture zones. Thus, it is possible to make the testing and implementation of the developed gravity gradient methods for detecting the fracture zones in the region of strike-slip fault.



(a) (b)

Fig. 4. (a) Area of study and its epicenter distribution of earthquakes in Palu Area; (b) Distribution of gravity measurements and geological map of the Palu Koro fault [9&10&11].

To identify the fracture zones, gravity data analysis has been conducted on complete Bouguer anomaly

(CBA). For each station of gravity measurements, the anomaly was derived using eq. *(4)*.

$$CBA = g_{obs} - g_e + FC - BC + TC \qquad (4)$$

where : g_{obs} is the observed gravity at station (or the value of gravity measurement after tidal and drift orrection were applied), g_e is ellipsoid gravity value at station, FC is free-air correction at station equal with 0.3045 /meter (in mGal), BC is Bouguer correction equal with $2\pi\rho_b\gamma h$ (in mGal), h is station elevation; γ is general gravity constant and TC is terrain correction.

After completing Bouguer anomaly calculation, the next process we need to conduct in gravity data processing is spectrum analysis to define window filter that will be used in filtering regional-residual gravity anomalies. The objective of this process is to split out the Bouguer gravity anomaly to become shallow and deep in gravity effects. The shallow effect is shown by residual anomaly, whilst deep effect is by regional anomaly.

For the purposes of analyzing the gravity responses in identifying fracture zones, the gravity and horizontal gradient anomalies caused by the density contrast changes of fracture zones have been analyzed based on the regional anomaly. The separation technique has been applied once again to obtain the residual anomaly contained in the regional anomaly. Furthermore, this residual gravity anomaly has been used as gravity anomaly which describes the density contrast changes of fracture zones in study area.

Horizontal gradient anomaly was obtained from gravity measurements at two different locations horizontally using a grid pattern. The determination of the horizontal gradient values used the concept of gradient interval [3]:

$$g_{zx} = \frac{g_x(2) - g_x(1)}{x_2 - x_1} \quad \text{and} \quad g_{zy} = \frac{g_y(2) - g_y(1)}{y_2 - y_1} \qquad (5)$$

Where: g_{zx} is horizontal gradient anomaly in the x-direction, g_{zy} is horizontal gradient anomaly in the y-direction.

Vertical gradient anomaly was obtained from gravity measurements at two different heights in which the second measurement was located vertically above the first measurement. Gravity measurements in the study area at two different heights have been performed using a tower with a height difference of 103 cm. The determination of the vertical gradient values used the concept of gradient interval [3]:

$$g_{zz} = \frac{g_z(2) - g_z(1)}{h_2 - h_1} \qquad (6)$$

3. Results and Discussions

In Fig. 5 shows the gravity and its gradient data that have been measured in Palu Koro fault, a segment of Palu City, Central Sulawesi, Indonesia. The gravity anomaly value of the study area is from -3.2 to 5 mGal with the low anomaly corresponding to the local faults which are influenced by the regional pattern of Palu Koro fault (Fig. 5a). Whilst the vertical gradient anomaly value of the study area is from -0.32 to 0.18 mGal/m in which the low anomaly lies in the north-western part (Fig. 5b). The negative vertical gradient anomaly in this area indicates the negative density contrast that may be caused by fracturing due to the tectonic activity of the Palu-Koro strike-slip fault, a segment of Palu.

Vertical gradient anomaly map shows a high sensitivity in detecting the boundaries of the smaller density contrast changes. In addition, the geometry of the small anomalies can be accurately identified with a higher resolution than when using gravity anomaly map. Although the vertical gradient has no sensitivity in detecting regional effects, the high resolution vertical gradient anomaly can be used as a controller in detecting the location and geometry of the shallow anomaly sources.

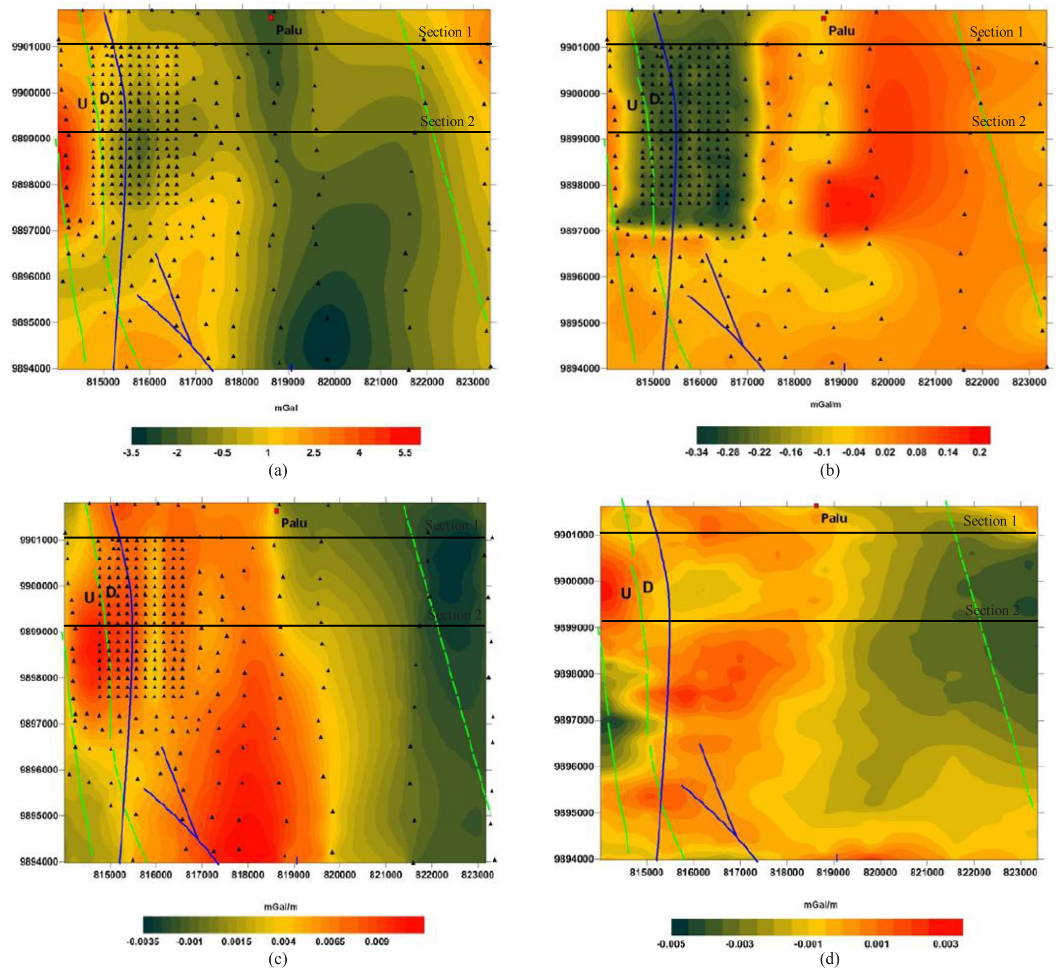
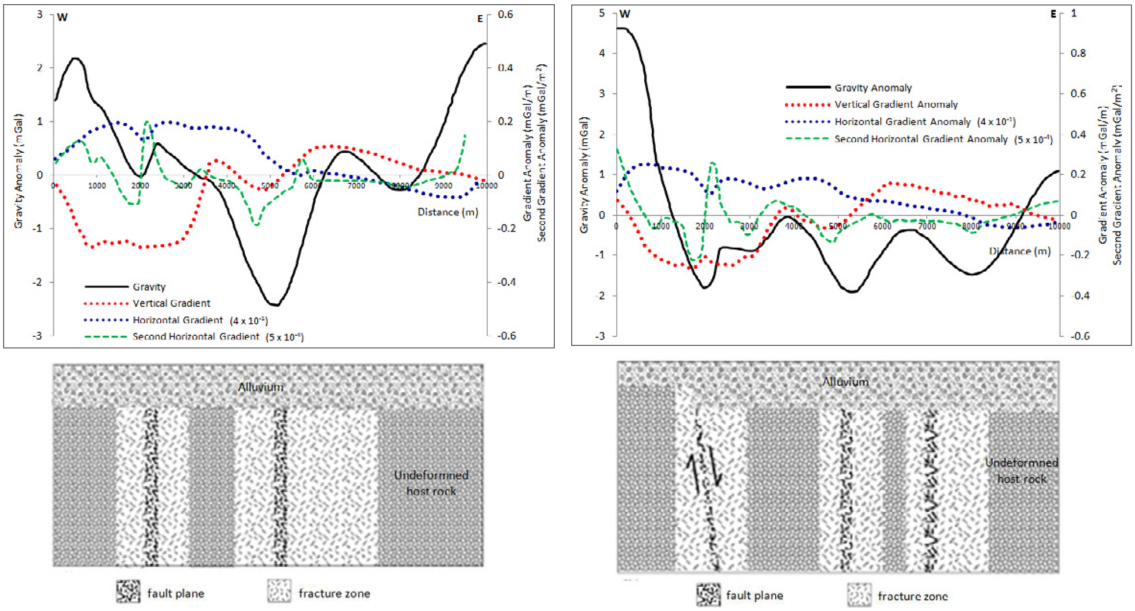


Fig. 5. (a) Gravity anomaly map of the Palu Koro fault and section 1 and 2 for the analysis of gravity gradient; (b) Vertical gradient anomaly map of the Palu Koro fault; (c) Horizontal gradient anomaly map in East-direction of the Palu Koro fault; (d) Horizontal gradient anomaly map in North-direction of the Palu Koro fault .

In Fig. 5c shows the horizontal gradient anomaly map in East-direction of Palu Koro fault. In general, the western part of study area has a positive horizontal gradient value between 0.011 to 0.013 mGal/m with an anomaly pattern that extends from South to North. Meanwhile, in the eastern part of the study area, the horizontal gradient anomaly also shows a North-South elongated pattern with negative values around -0.001 to -0.0036 mGal/m. The detail symmetry patterns of positive and negative anomalous values in this area indicate that there are the boundaries of density contrast changes due to fracture zones in the Palu Koro strike-slip fault.

Horizontal gradient anomaly map in North-direction of the Palu Koro fault (Fig. 5d) also demonstrates a symmetry pattern with positive and negative anomalous values. However, it appears that the density contrast changes in North-South direction is less significant than the East-West direction. This indicates that the density contrast change in this area is dominant in the East-West direction due to Palu Koro fault activity with North-South movement.

Further analysis of the gravity and its gradient responses are carried out by analyzing two sections of gravity and its gradient anomalies. The measurement result shows that the gravity gradients have a higher sensitivity compared to its gravity anomaly in detecting the fracture zones. Based on the analysis of gravity and its gradient responses using section 1 and 2 (in Fig. 6), the result demonstrates the suitability of responses patterns as it has been built on forward modelling. Therefore, the fracture zones at the study area can be identified based on those criteria.



(a) (b)

Fig. 6. (a) Gravity and its gradient responses for section 1 of Palu Koro fault; (b) Gravity and its gradient responses for section 2 of Palu Koro fault.

Finally, we have implemented the inversion technique to gravity and its gradient data. The rms error value and the iteration number of the inversion results of gravity gradients data are less when using its gravity anomaly inversion. The inversion result of the gravity gradients anomaly shows that the boundaries of lateral changes in the distribution of density contrast of fracture zones can be identified more accurately than when using its gravity anomaly inversion.

The inversion result (in Fig. 7) shows that the contrast density distribution of fracture zones in the region of Palu Koro fault, segment of Palu City, is at intervals from -0.2 to 0.13 gram/cm^3. The direction and density contrast distribution of fracture zones in Palu Koro fault generally have pattern that extends from North to South. Based on the distribution of density contrast, segment of the Palu City can be divided into three fracture zones. These fractures zones are suspected as local faults which are influenced by the regional pattern of Palu Koro fault that extends from North to South.

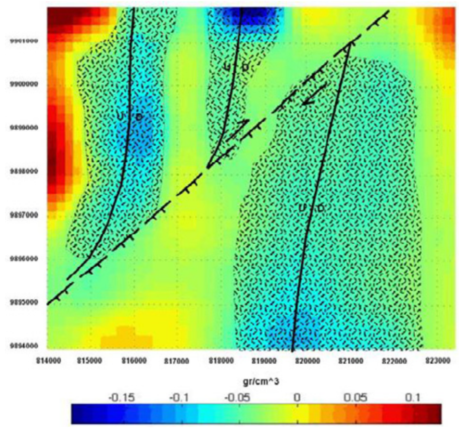


Fig. 7. Density contrast distribution map of fracture zones in the region of the Palu Koro fault identified by inversion result .

4. Conclusions

Gravity gradient technique can be used for detecting the fracture zones in a strike-slip fault system as can be found in the region of the Palu Koro fault with a higher sensitivity compared to its gravity anomaly. Inversion result shows that the distribution of the density contrast in the study area consists of three fracture zones which are interpreted as local faults due to the tectonic activity of the Palu Koro strike-slip fault.

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